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PATENT APPLICATION

of

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for

COUPLED BAW RESONATOR BASED DUPLEXERS

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COUPLED BAW RESONATOR BASED DUPLEXERS

Field of the Invention

The present invention relates generally to bulk acoustic wave resonators and filters and, more particularly, to bulk acoustic wave baluns used in filters and duplexers.

Background of the Invention

It is known that a bulk acoustic-wave (BAW) device is, in general, comprised of a piezoelectric layer sandwiched between two electronically conductive layers that serve as electrodes. When a radio frequency (RF) signal is applied across the device, it produces a mechanical wave in the piezoelectric layer. The fundamental resonance occurs when the wavelength of the mechanical wave is about twice the thickness of the piezoelectric layer. Although the resonant frequency of a BAW device also depends on other factors, the thickness of the piezoelectric layer is the predominant factor in determining the resonant frequency. As the thickness of the piezoelectric layer is reduced, the resonance frequency is increased. BAW devices have traditionally been fabricated on sheets of quartz crystals. In general, it is difficult to achieve a device of high resonance frequency using this fabrication method. When fabricating BAW devices by depositing thin-film layers on passive substrate materials, one can extend the resonance frequency to the 0.5 – 10 GHz range. These types of BAW devices are commonly referred to as thin-film bulk acoustic resonators or FBARs. There are primarily two types of FBARs, namely, BAW resonators and stacked crystal filters (SCFs). An SCF usually has two or more piezoelectric layers and three or more electrodes, with some electrodes being grounded. The difference between these two types of devices lies mainly in their structure. FBARs are usually used in combination to produce passband or stopband filters. The combination of one series FBAR and one parallel, or shunt, FBAR makes up one section of the so-called ladder filter. The description of ladder filters can be found, for example, in *Ella* (U.S. Patent No. 6,081,171, hereafter referred to as *Ella'171*). As disclosed in *Ella'171*, an FBAR-based device may have one or more protective layers commonly referred to as the passivation layers. A typical FBAR-based device is shown in Figures 1a to 1d. As shown in Figures 1a to 1d, the FBAR device comprises a substrate **501**, a bottom electrode **507**, a piezoelectric layer **509**, and a top electrode **511**. The electrodes and the piezoelectric layer form an acoustic resonator. The FBAR device may additionally include a membrane layer

505. As shown in Figure 1a, an etched hole **503** is made on the substrate **501** to provide an air interface, separating the resonator from the substrate **501**. Alternatively, an etched pit **502** is provided on the substrate **501**, as shown in Figure 1b. It is also possible to provide a sacrificial layer **506** separating the resonator and the substrate, as shown in Figure 1c. It is also possible to form an acoustic mirror **521** between the bottom electrode **507** and the substrate **501** for reflecting the acoustic wave back to the resonator, as shown in Figure 1d. The substrate can be made from silicon (Si), silicon dioxide (SiO_2), Gallium Arsenide (GaAs), glass or ceramic materials. The bottom electrode and top electrode can be made from gold (Au), molybdenum (Mo), tungsten (W), copper (Cu), nickel (Ni), titanium (Ti), Niobium (Nb), silver (Ag), tantalum (Ta), cobalt (Co), aluminum (Al) or a combination of these metals, such as tungsten and aluminum. The piezoelectric layer **130** can be made from zinc oxide (ZnO), zinc sulfide (ZnS), aluminum nitride (AlN), lithium tantalate ($LiTaO_3$) or other members of the so-called lead lanthanum zirconate titanate family. Additionally, a passivation layer typically made from a dielectric material, such as SiO_2, Si_3N_4, or polyimide, is used to serve as an electrical insulator and to protect the piezoelectric layer. It should be noted that the sacrificial layer **506** in a bridge-type BAW device, as shown in Figure 1c, is, in general, etched away in the final fabrication stages to create an air interface beneath the device. In a mirror-type BAW device, as shown in Figure 1d, the acoustic mirror **521** consists of several layer pairs of high and low acoustic impedance materials, usually a quarter-wave thick. The bridge-type and the mirror-type BAW devices are known in the art.

It is also known in the art that FBARs can be used to form impedance element filters in a ladder filter configuration that has unbalanced input and output ports, or in a lattice filter configuration that has balanced ports. In some applications it would be advantageous to transform an unbalanced input to a balanced output (or vice versa) within a filter. Such filters have been produced using acoustically coupled surface acoustic wave (SAW) resonators. Basically these structures are based on a pair of resonators, as shown in Figure 2. As shown, the first resonator **620** generates the acoustic wave and the second resonator **630** acts as a receiver. Since the resonators are not electrically connected, one of them can be connected as an unbalanced device and the other can be used in either as a balanced or an unbalanced device. As shown in Figure 2, the first resonator **620** provides an unbalanced port **622** for signal input, whereas the second resonator **630** provides two ports **632, 634** for balanced signal outputs. As shown, numerals **610** and **640** denote

reflectors or acoustic mirrors for the surface acoustic wave device. This same principle can be used in a BAW device having a structure that has two piezoelectric layers, one on top of each other. Using such a structure, it is possible to perform this unbalanced-to-balanced transformation. This structure can then be used as part of a filter or even a duplexer. One possible way of realizing such a structure is described in "High Performance Stacked Crystal Filters for GPS and Wide Bandwidth Applications", *K.M. Lakin, J. Belsick, J.F. McDonald, K.T. McCarron*, IEEE 2001 Ultrasonics Symposium Paper 3E-6, October 9, 2001 (hereafter referred to as *Lakin*). Figure 3 is a coupled resonator filter (CRF) disclosed in *Lakin*. As shown in Figure 3, the CRF is formed by a bottom electrode **507**, a bottom piezoelectric layer **508**, a cross-over electrode **511**, a plurality of coupling layers **512**, a ground electrode **513**, a top piezoelectric layer **509** and two separate top electrodes **531** and **532**. As such, the CRF has a first vertical pair **541** of resonators and a second vertical pair **542** of resonators. Each of the vertical pairs acts as a one-pole filter. In series, the two vertical pairs act as a two-pole filter. The CRF is made on a substrate **501** separated by an acoustic mirror **521**.

Ella et al. (U.S. Patent No. 6,670,866 B2, hereafter referred to as *Ella'866*) discloses a BAW device with two resonators and a dielectric layer therebetween. As shown in Figure 4, the BAW device **20** is formed on a substrate **30** and comprises a first electrode **40**, a first piezoelectric layer **42**, a second electrode **44** connected to the device ground **12**, a third electrode **60**, a dielectric layer **50** between the second electrode **44** and the third electrode **60**, a second piezoelectric layer **62** and a fourth electrode **64**. The first electrode **40**, the first piezoelectric layer **42** and the second electrode **44** have an overlapping area for forming a first resonator **92**. The third electrode **60**, the second piezoelectric layer **62** and the fourth electrode **64** have an overlapping area for forming a second resonator **94**. The bulk acoustic wave device **20** has a resonant frequency and an acoustic wavelength, λ, characteristic of the resonant frequency. The thickness of the first and second piezoelectric layers **42, 62** is substantially equal to $\lambda/2$. Furthermore, the device **20** has an acoustic mirror **34** formed between the first electrode **40** and the substrate **30** to reflect acoustic waves back to the first resonator **92**. As shown in Figure 4, a section of the first electrode **40** is exposed for use as a connection point to the signal input end **14** of a balun **10** (see Figure 5). Similarly, a section of the second electrode **44** is exposed for use as a connection point to the device ground **12**. The first resonator **92** and the second resonator **94** have an overlapping area **70**, defining an active area of the

bulk acoustic wave device **20**. The device **20** has a first signal output end **16** and a second signal output end **18**.

Ella '886 also discloses a balun for use in applications with lower bandwidth requirements. As shown in Figure 5, the balun **10** has two identical stacks **21, 21'** of layers, similar to the bulk acoustic wave device **20** of Figure 4. However, the first electrode **40'** and the third electrode **60'** of the layer stack **21'**, and the second electrode **44** and the third electrode **60** of the layer stack **20** are connected to ground **12**. In addition, the second electrode **44'** of the layer stack **21'** is connected to the first electrode **40** of the layer stack **21** and is used as the signal input end **14**. The top electrode **64** of the layer stack **21** is used as the first signal output end **16**, while the top electrode **64'** of the layer stack **21'** is used as the second signal output end **18**. With the double-structure, there is no need for the compensation capacitance because the electrodes **60, 60'** below the upper piezoelectric layers **62, 62'** are grounded. This electric shielding effect results in the symmetric impedance for the first and second signal output ends **16, 18**. The parasitic capacitance of the dielectric layers **50, 50'** is parallel to the signal input end **14**. This parasitic capacitance somewhat degrades the bandwidth of the device but does not harm its symmetry. The cross-connected input electrodes **40, 44'** generate a perfect 180° phase between the acoustic waves in the stack **21** and the stack **21'**.

Ella '886 also discloses that the balun **10** can be used as part of a filter that has one unbalanced port and two balanced ports. Two baluns **10** can be coupled to lattice filters **150** to form a duplexer **201** as shown in Figure 6. In Figure 6, a phase shifter **242** is used for filter matching. Similarly, two baluns **10** can be coupled to one lattice filter **150** and one ladder filter **250** to form a duplexer **203**, as shown in Figure 7.

It is also possible to form a simple duplexer by using two single-ended ladder filters and a phase shifter, as shown in Figure 8. As shown in the figure, a single-ended ladder filter **260** is used for Tx and another single-ended ladder filter **262** is used for Rx. However, it usually requires that some inductance components, such as coils, to be connected in series with some of the shunt resonators in the Tx filter order to shift the natural notch to coincide with the Rx frequency. These coils not only cause additional losses in the duplexer, but also create other higher resonance frequencies, further degrading the overall out-of-band attenuation of a single-ended filter. In order to reduce the out-of-band attenuation in the Rx path, it is possible to combine a fully balanced Rx filter with a single-ended Tx filter, as shown in Figure 9. As shown in Figure 9, the fully

balanced Rx filters **270** are connected to a pair of connected (in series) baluns. The problem with this approach is that any loss associated with the baluns at the antenna port will also cause losses in the Tx path. The Tx path also suffers from the degraded out-of-band due to the inductance.

It is thus advantageous and desirable to provide a simple duplexer that does not have the above-mentioned disadvantageous.

Summary of the Invention

The present invention uses a coupled resonator filter in the transmit path of a duplexer and another coupled resonator filter in the receive path. The coupled resonator filter in the transmit path has a single-ended input port and a single-ended output port, whereas the coupled resonator filter in the receive path has a single-to-balanced transformation.

Thus, the first aspect of the present invention provides a duplexer for use in a communication device, the communication device having

an antenna for conveying communication signals;

a transmit path operatively connected to the antenna for transmitting the signals; and

a receive path operatively connected to the antenna for receiving the signals. The duplexer comprises:

a first coupled resonator device disposed in the transmit path for filtering the signals in the transmit path;

a second coupled resonator device disposed in the receive path for filtering the signals in the receive path; and

a phase shifter disposed in the receive path and operatively connected to the second coupled resonator device, wherein each of said first and second coupled resonator devices comprises:

an input end for receiving the signals in the corresponding path, and an output end for providing filtered signals in the corresponding path;

a first resonator operatively connected to the input end to provide acoustic wave signals indicative of the received signals;

a first delay section, responsive to the acoustic wave signals, for providing delayed acoustic wave signals;

an intermediate resonator having a first end and a second end, responsive to the delayed acoustic wave signals at the first end, for producing at the first and second ends electric signals indicative of the delayed acoustic wave signals for generating further acoustic wave signals at the second end;

a second delay section, responsive to the further acoustic wave signals, for proving further delayed acoustic wave signals; and

a second resonator operatively connected to the output end, for providing the filtered signals to the output end responsive to the further delayed acoustic wave signals.

According to the present invention, the phase shifter is disposed between the second coupled resonator device and the antenna.

According to the present invention, the communication device may comprise a further phase shifter disposed in the transmit path and operatively connected to the first coupled resonator device, wherein the further phase shifter is disposed between the first coupled resonator device and the antenna.

Alternatively, the first coupled resonator device is disposed between the further phase shifter and the antenna.

According to the present invention, the input end of the first coupled resonator device comprises two input terminals, and the output end of the first coupled resonator device comprises two output terminals, and wherein one of the two input terminals and one of the two output terminals are operatively connected to ground.

According to the present invention, the input end of the second coupled resonator comprises two input terminals, and wherein one of the two input terminals is operatively connected to ground to achieve a single-to-balanced transformation.

According to the present invention, the first and second resonators are bulk acoustic wave devices. Each of the first and second delays comprises a transmission line or one or more lump elements. These non-acoustic delays may be integrated into the coupled resonator devices.

The second aspect of the present invention provides a coupled resonator device, which comprises:

an input end for receiving the signals in the corresponding path, and an output end for providing filtered signals in the corresponding path;

a first resonator, operatively connected to the input end to provide acoustic wave signals indicative of the received signals;

a first delay section, responsive to the acoustic wave signals, for providing delayed acoustic wave signals;

an intermediate resonator having a first end and a second end, responsive to the delayed acoustic wave signals at the first end, for producing electric signals at the first and second ends indicative of the delayed acoustic wave signals for generating further acoustic wave signals at the second end;

a second delay section, responsive to the further acoustic wave signals, for proving further delayed acoustic wave signals; and

a second resonator, operatively connected to the output end, for providing the filtered signals to the output end responsive to the further delayed acoustic wave signals.

According to the present invention, the resonator device has a substrate and the intermediate resonator comprises:

a first electrode disposed on the substrate;

a piezoelectric layer disposed on the first electrode; and

a second electrode disposed on the piezoelectric layer, the second electrode having a first end and a second end, and wherein

the first delay section is disposed on the first end of the second electrode;

the second delay section is disposed on the second end of the second electrode;

the first resonator is disposed on the first delay section; and

the second resonator is disposed on the second delay section.

According to the present invention, each of the first and second resonators comprises a pair of electrodes and a further piezoelectric layer disposed between said pair of electrodes.

According to the present invention, the resonator device may have an acoustic mirror disposed adjacent to the intermediate resonator, between the first electrode and the substrate.

Each of the first and second delay sections comprises a plurality of dielectric materials, or a structure composed of silicon dioxide and tungsten layers.

According to the present invention, the input end comprises two input terminals, wherein one of the two input terminals is operatively connected to ground and the other input terminal is optionally connected to a phase shift component.

According to the present invention, the first resonator has a first resonant frequency, and the second resonator has a second resonant slightly different from the first resonant frequency.

The third aspect of the present invention provides a communication device, which comprises:

an antenna port for conveying communication signals;

a transceiver having a transmit port and a receive port; and

a duplexer comprising:

a first coupled resonator device disposed in a transmit path between the antenna port and the transmit port for filtering the signals in the transmit path;

a second coupled resonator device disposed in the receive path between the antenna port and the receive port for filtering the signals in the receive path; and

a phase shifter disposed in the receive path and operatively connected to the second coupled resonator device, wherein each of said first and second coupled resonator devices comprises:

an input end for receiving the signals in the corresponding path; and an output end for providing filtered signals in the corresponding path;

a first resonator, operatively connected to the input end, for providing acoustic wave signals indicative of the received signals;

a first delay section, responsive to the acoustic wave signals, for providing delayed acoustic wave signals;

an intermediate resonator having a first end and a second end, responsive to the delayed acoustic wave signals at the first end, for producing an electric signals at the first and second ends indicative of the delayed acoustic wave signals for generating further acoustic wave signals at the second end;

a second delay section, responsive to the further acoustic wave signals, for proving further delayed acoustic wave signals; and

a second resonator operatively connected to the output end, for providing the filtered signals to the output end responsive to the further delayed acoustic wave signals.

According to the present invention, the first coupled resonator device has a single-to-single configuration and the second coupled resonator device has a single-to-balance transformation.

According to the present invention, the duplexer may include a further phase shifter disposed in the transmitted path and operatively connected to the first coupled resonator device.

According to the present invention, each of the phase shifter and the further phase shifter comprises a transmission line or a lump element, which may be integrated into the resonator devices.

The communication device can be a mobile terminal, a communicator device or the like.

The present invention will become apparent upon reading the description taken in conjunction with Figures 10 – 13.

Brief Description of the Drawings

Figure 1a is a cross-sectional view illustrating a typical bulk acoustic wave device having a resonator and a membrane formed on a substrate, wherein the substrate has a through hole for providing an air interface for the membrane.

Figure 1b is a cross-sectional view illustrating a typical bulk acoustic wave device having a resonator and a membrane formed on a substrate, wherein the substrate has an etched section for providing an air interface for the membrane.

Figure 1c is a cross-sectional view illustrating a typical bulk acoustic wave device having a resonator and a membrane formed on a substrate, wherein a sacrificial layer is formed between the membrane and the substrate.

Figure 1d is a cross-sectional view illustrating a typical bulk acoustic wave device having a resonator formed on a substrate, wherein an acoustic mirror is formed between the substrate and the bottom electrode of the resonator.

Figure 2 is a schematic representation showing a prior art arrangement, wherein two resonators are used to transform unbalanced signals to balanced signals.

Figure 3 is a cross sectional view illustrating a prior art arrangement of a coupled resonator filter, wherein two crystal filter resonators are horizontally spaced.

Figure 4 is a schematic representation showing a prior art balun with one signal input port and two signal output ports.

Figure 5 is a schematic representation showing a prior art balun with two filter stacks.

Figure 6 is a block diagram showing a prior art duplexer wherein each of the transceiver filters has a balun and a lattice filter segment.

Figure 7 is a block diagram showing a prior art duplexer, wherein one transceiver filter has a balun coupled to a lattice filter segment, and the other transceiver filter has a balun coupled to a ladder filter.

Figure 8 is a block diagram showing a prior art duplexer with two single-ended filters.

Figure 9 is a block diagram showing a prior-art duplexer with a single-ended filter and a fully balanced filter.

Figure 10 is a schematic representation showing the coupled BAW resonator, according to the present invention.

Figure 11 is a block diagram illustrating the acoustic and electrical coupling in the coupled BAW resonator.

Figure 12a is a block diagram showing a duplexer, according to an embodiment of the present invention.

Figure 12b is a block diagram showing the duplexer, according to another embodiment of the present invention.

Figure 12c is a block diagram showing the duplexer, according to yet another embodiment of the present invention.

Figure 13 is a schematic representation showing a communications device having a duplexer, according to the present invention.

<u>Best Mode to Carry Out the Present Invention</u>

The duplexer, according to the present invention, is based on coupled BAW resonator devices. The coupled resonator device is shown in Figure 10. The coupled resonator device **700** comprises a coupled resonator filter (CRF) **710** coupled to another CRF **720**. As shown in Figure 10, the resonator device **700** comprises a substrate **730**, a lower resonator **740**, a first delay **752**, a second delay **754**, a first upper resonator **760** and a second upper resonator **770**. The lower resonator **740** comprises a bottom electrode **742**, an upper electrode **746** and a piezoelectric layer **744** disposed between the electrodes **742** and **746**. The first delay **752** and the second delay **754**, which are separately disposed on top of the lower resonator **740**, are composed of a plurality of layers of different dielectric materials. The structure of the first delay **752** and the second delay **754** can be

$SiO_2/W/SiO_2$, for example. The first upper resonator **760**, which is disposed on top of the first delay **752**, comprises a bottom electrode **762**, an upper electrode **766** and a piezoelectric layer **764** therebetween. The second upper resonator **770**, which is disposed on top of the first delay **754**, comprises a bottom electrode **772**, an upper electrode **776** and a piezoelectric layer **774** therebetween. The resonator device **700** may comprise an acoustically reflecting membrane with a cavity (see Figure 1a), a sacrificial layer (see Figure 1c), or an acoustic mirror **734** under the lower resonator **740**. One of the upper resonators is used as a signal input port and the other is used as a signal output port. As shown in Figure 10, the electrodes **766, 762** are connected to terminals **72** and **74**; and the electrodes **776, 772** are connected to terminals **76** and **78**. If first upper resonator **760** is used to excite an acoustic wave by an electric signal through terminals **72, 74**, the acoustic wave propagates to the lower resonator **740** through the first delay **752**. At the lower resonator **740**, the acoustic wave in the piezoelectric layer **744** is converted into electrical signal. The electrical signal in the electrodes **742, 746** is again converted into an acoustic wave, which propagates to the second upper resonator **770** through the second delay **754**. At the resonator **770**, the acoustic wave is converted back to an electric signal at the terminals **76, 78**. The acoustic excitation within the CRF **710** and CRF **720**, and electrical coupling between them is shown in Figure 11. The first upper resonator **760** and the second upper resonator **770** typically exhibit slightly different resonant frequencies in order to shape the passband response.

The resonator device **700**, according to the present invention, can be used in a duplexer as shown in Figure 12a. As shown, the duplexer **800** comprises a Tx part and an Rx part separately connected to a Tx port and an Rx port, respectively. In the Rx part, the resonator device **700** is used as a single-to-balanced filter in that the terminal **74** is connected to ground. The resonator **700** is connected to a common antenna port through a phase shifter **810**. In the Tx part, the resonator device **700'** is used as a single-to-single filter in that both the terminal **74'** and terminal **78'** are connected to ground. The resonator **700'** is connected to the common antenna port through a phase shifter **810'**. The phase shifters **810** and **810'** can be made of transmission lines, lump elements such as inductors and coils, or the like. The phase shifters **810, 810'** can be integrated with the corresponding resonator devices **700, 700'** if plausible. Furthermore, the phase shifter **810'** can be disposed between the resonator device **700'** and the Tx port, as shown in Figure 12b. It is possible to omit the phase shifter **810'** in the Tx part, as shown in Figure

12c. Depending on the guard bandwidth between the Tx part and Rx part, the duplexer **800** can be used in a W-CDMA or CDMA transceiver.

The duplexer **800**, according to the present invention, can be used in a communications device, such as a mobile phone, as shown in Figure 13. As shown, the duplexer **800** is operatively connected to the Rx and Tx ports of the transceiver **900** in the communications device **1**.

It should be noted that the resonator device **700** as shown in Figure 10 has two CRF stages, but can have more than two CRF stages. Similarly, the resonator device **700** in the Rx part and the resonator device **700'** can be coupled to other CRF stages or other similar resonator devices, depending on the frequency selectivity requirements of the transceiver. If necessary, one or more phase shifters, similar to the phase shifter **242** in Figures 6 and 7, can be used for matching. The phase shifters can be based on lump elements (such as inductors and coils), or microstrip lines on the duplexer substrate, which may be organic laminate or LTCC (low-temperature cofire ceramic), for example.

The advantages of the duplexer, according to the present invention, include that the out-of-band attenuation far from the passband is greatly improved over the convention duplexers, and that the losses seen at both the Rx and Tx paths are reduced because no magnetic balun is required for the fully balanced Rx part. It should also be noted that impedance level transformation is possible in the duplexer, according to the present invention.

Although the invention has been described with respect to a preferred embodiment thereof, it will be understood by those skilled in the art that the foregoing and various other changes, omissions and deviations in the form and detail thereof may be made without departing from the scope of this invention.